Overland Millimeter-wave Retrievals of Total Column Water Vapor

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Overland Total Column Water Vapor Radiometer
Alan Tanner

- Problem: Conventional downward viewing mm-wave atmospheric soundings can't measure water in lower troposphere over land (Due to high surface emissivity, insufficient land - air temperature difference, and unknown scattering)

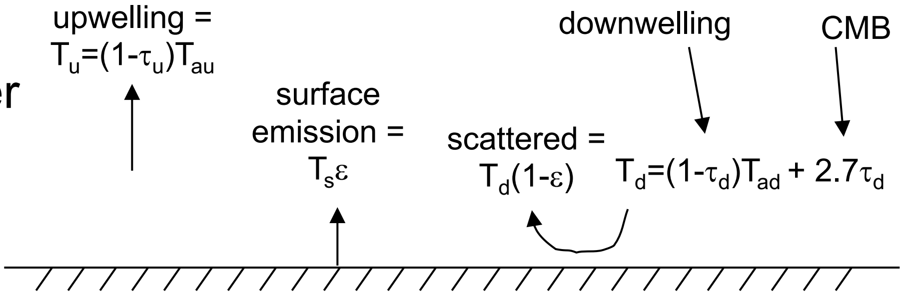
- Solution: New technique measures water relative to oxygen by matching image contrasts among bands between 118 and 183 GHz.

- Tested using data from Colorado State University 'HAMMR' radiometer aboard Twin-Otter aircraft.

Problem:

Microwave Water Vapor Retrievals presently of two kinds:

1) 18, 23, 34 GHz ideal for total vapor over oceans
   - Enabled by high ocean surface reflection
   - Won't work over land



2) Vertical sounding / profiling near 183 GHz
   - High opacity and high temperature lapse rate provide good sounding above lower troposphere
   - Lower troposphere obscured over land
   - Yet most water is in lower troposphere!

Over land:

Emissivity and surface temperature highly variable

Unknown surface scattering leads to unknown mix of one-way versus two-way path through atmosphere

Proposed solution:

Use known oxygen absorption as a reference to estimate opacity due to water vapor

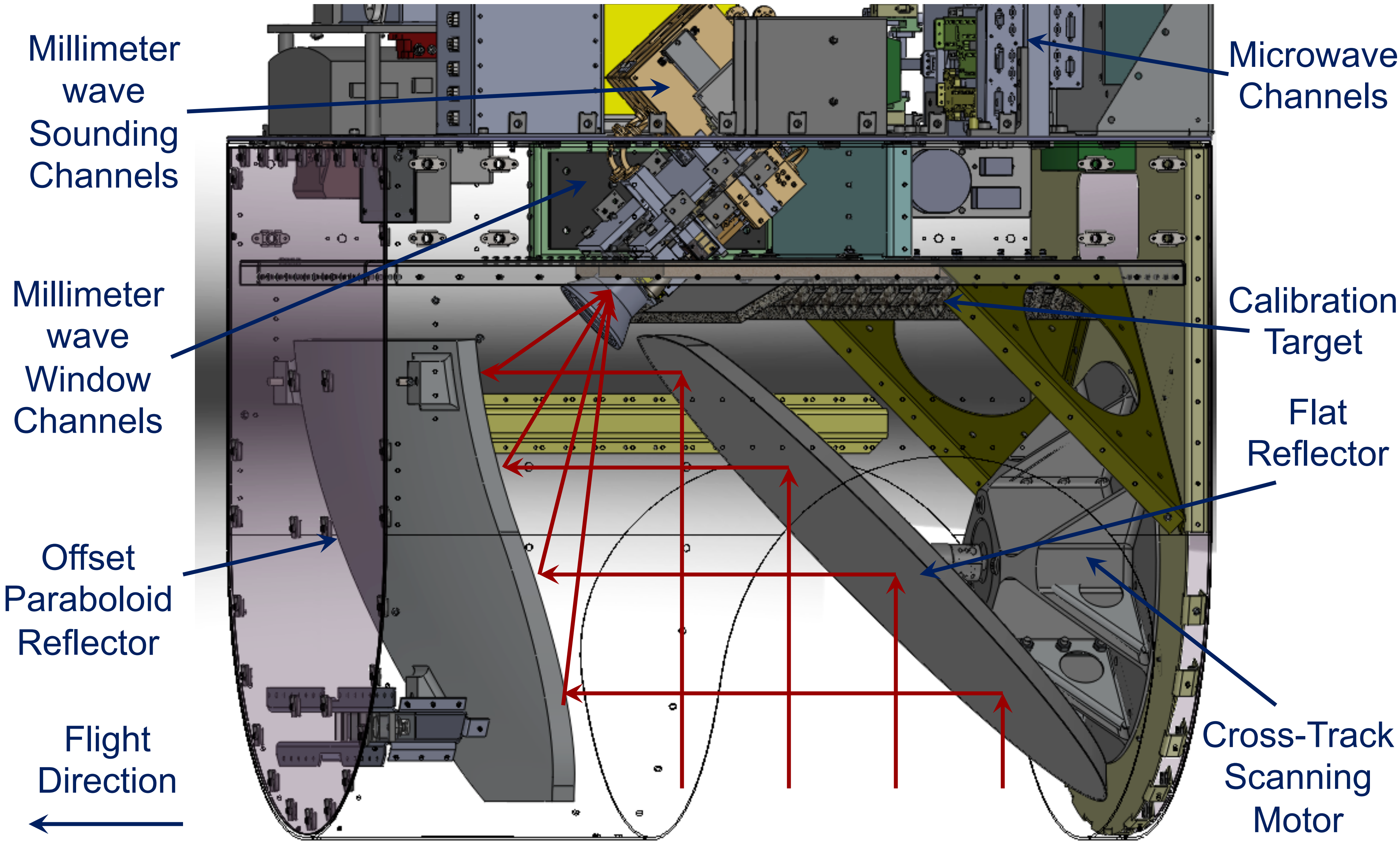
Compare images of the land in bands above 118 GHz with coincident images below 183 GHz

To first order, atmosphere is treated as simple attenuating “slab”

Two “slabs” of equal opacity and temperature will attenuate and emit equally, so land images will also be equal– regardless of surface scattering or emission.

Process is analogous to comparing two pieces of tinted glass: You can judge when two pieces have the same ‘darkness’ or attenuation, even if you don’t have any other objective measure of the scene behind the glass.

Colorado State University HAMMR Instrument

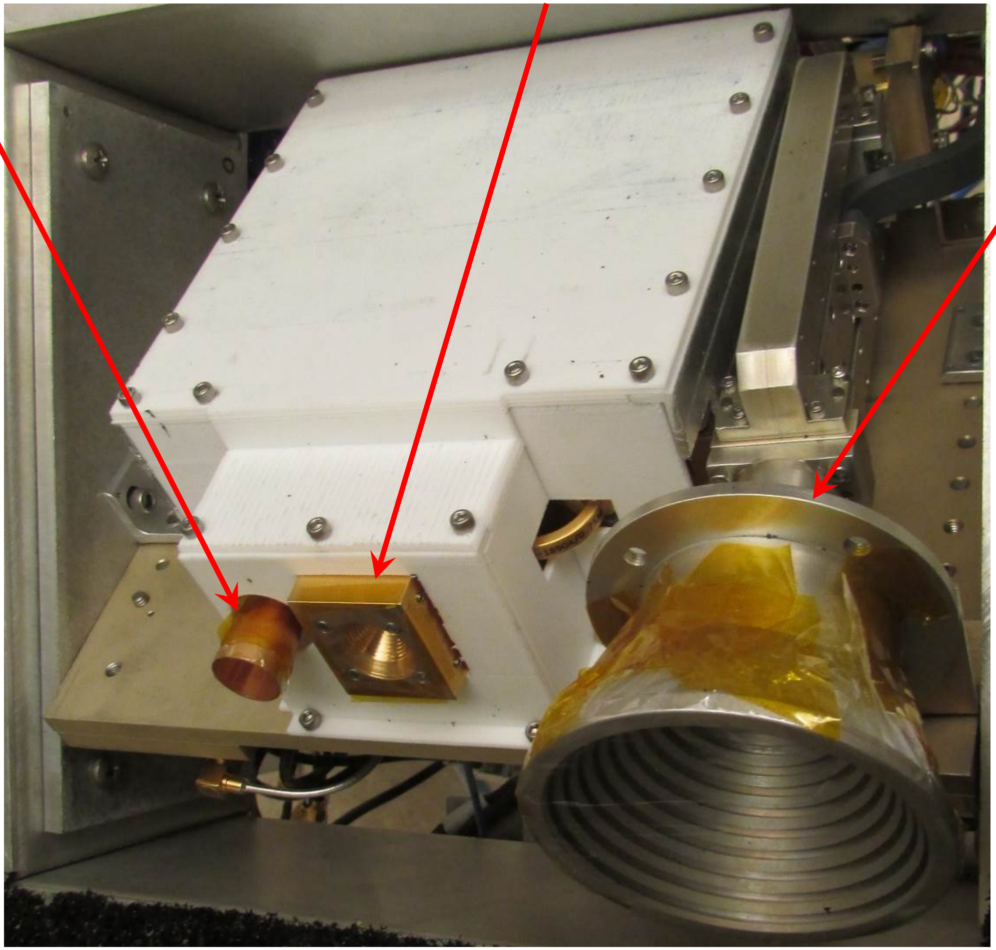


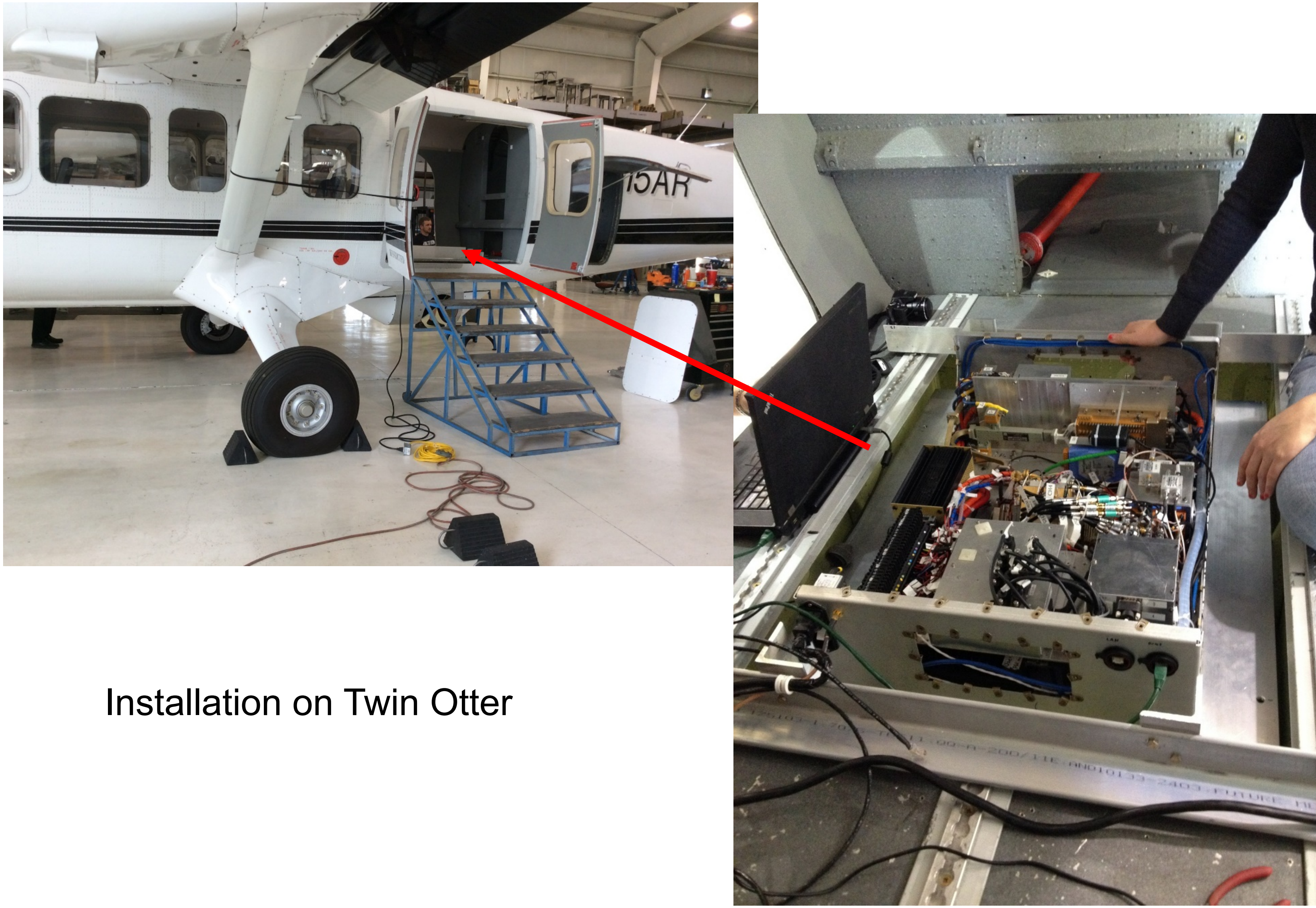
Three Feed Horn Antennas for Three Frequency Channel Sets

High-Frequency Millimeter-wave Sounding Channels (118 and 183 GHz)

High-Frequency Millimeter-Wave Window Channels (90, 130 and 168 GHz)

Low-Frequency Microwave channels (18.7, 23.8 and 34 GHz)





Installation on Twin Otter

Field Campaign

HAMMR installation
at TOI, Grand
Junction, CO
Nov 03, 2014

Salem , OR
Nov 10, 2014

Pre-flight LN2 Calibration Salem , OR
Nov 10, 2014

HAMMR channels

Radiometer	Frequency	Internal Target Standard Deviation	Pyramidal Target Standard Deviation
Microwave QV	18.7 GHz	0.3	0.3
	23.8 GHZ	0.2	0.1
	34.0 GHz	0.3	0.4
Microwave QH	18.7 GHz	0.4	0.5
	23.8 GHZ	0.3	0.2
	34.0 GHz	0.2	0.1
Millimeter-Wave Window	90 GHz	0.2	0.2
	130 GHz	N/A	N/A
	168 GHz	0.6	1
Millimeter-Wave Sounding 118.75 GHz	0 MHz	N/A	N/A
	250 MHz	0.4	0.6
	500 MHz	0.2	0.5
	+1 GHz	0.2	0.2
	+2 GHz	0.3	0.5
	+3 GHz	0.3	0.5
	+4 GHz	0.3	0.7
	+5 GHz	0.2	0.7
	+6 GHz	N/A	N/A
	+7 GHz	N/A	N/A
	+8 GHz	N/A	N/A
Millimeter-Wave Sounding 183.31 GHz	-1GHz	0.4	0.5
	-2 GHz	0.3	0.4
	-3 GHz	0.4	0.3
	-4 GHz	0.3	0.2
	-5 GHz	0.2	0.4
	-6 GHz	0.3	0.3
	-7 GHz	0.4	0.3
	-8 GHz	0.2	0.4

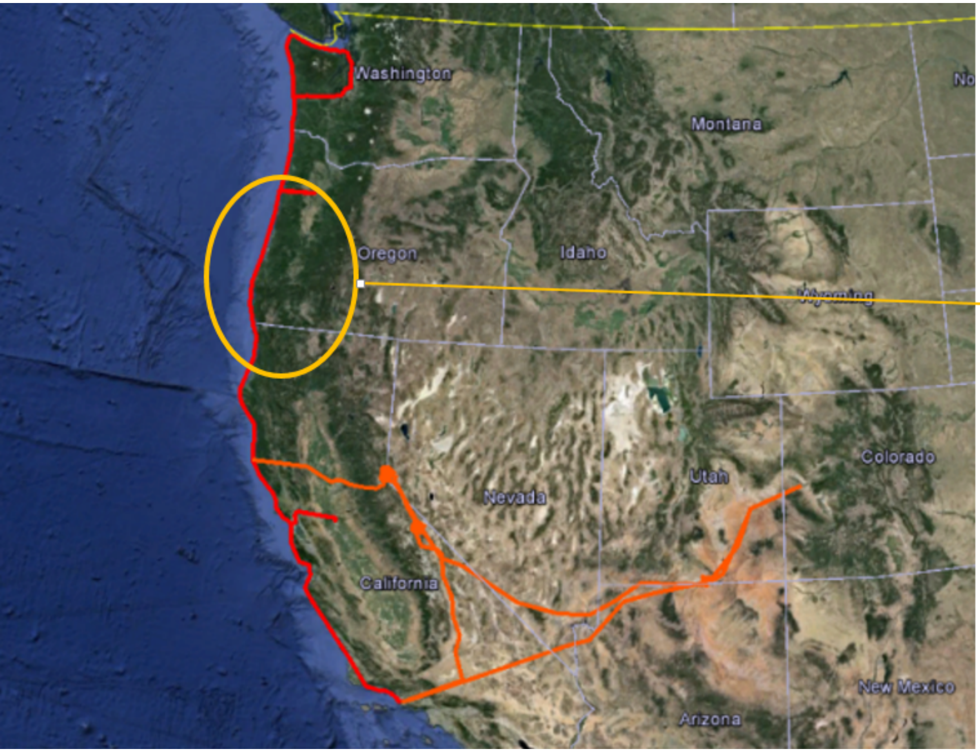
19,24,34 GHz microwave

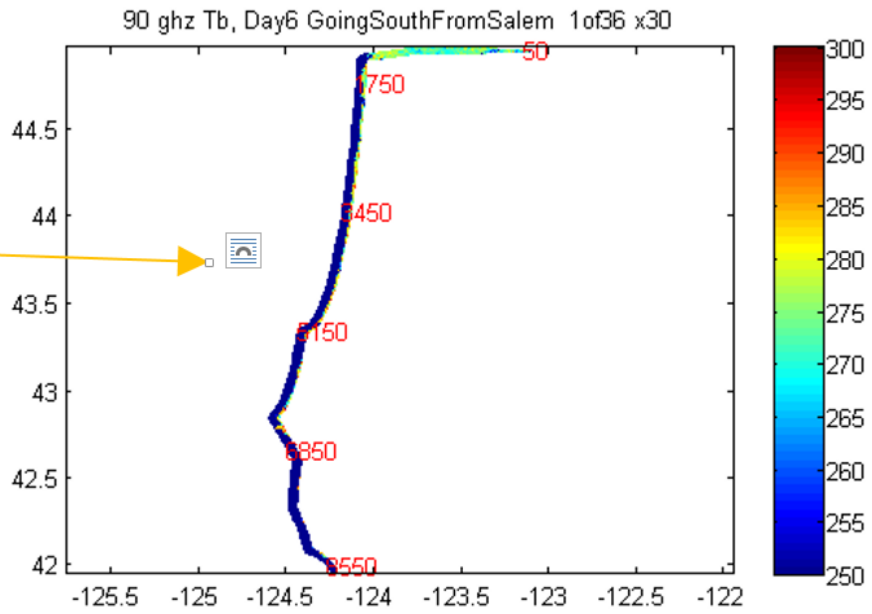
90, 130, 168 GHz mmw window bands

118-126 GHz oxygen sounding

175-183 GHz water vapor sounding

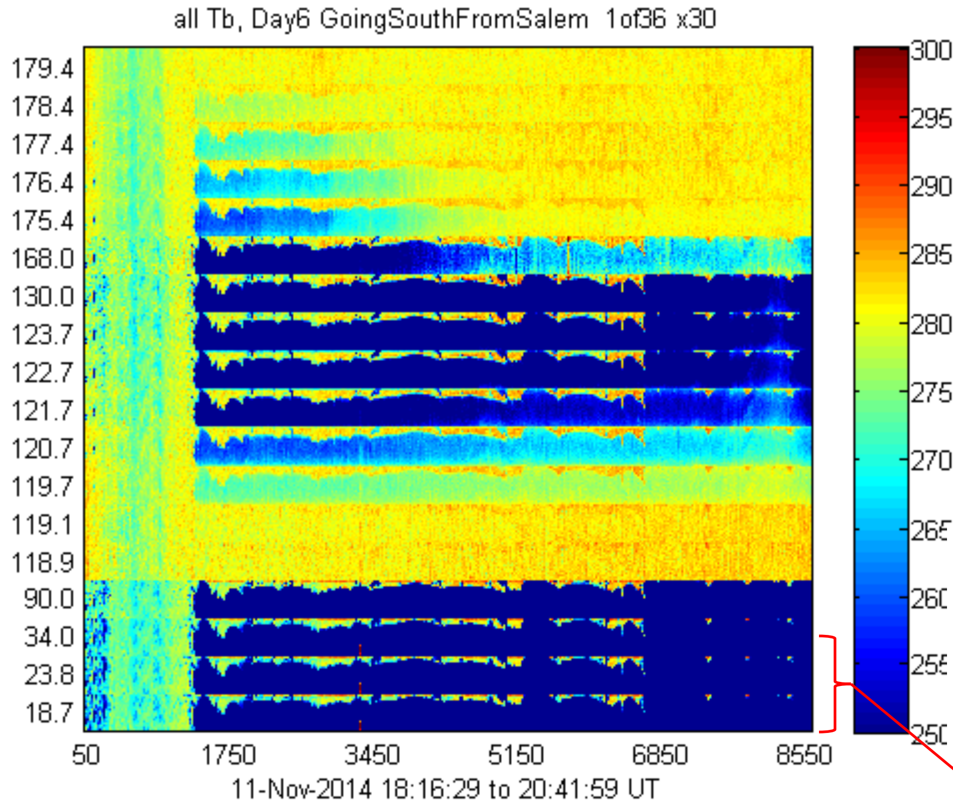
November, 2014 field campaign



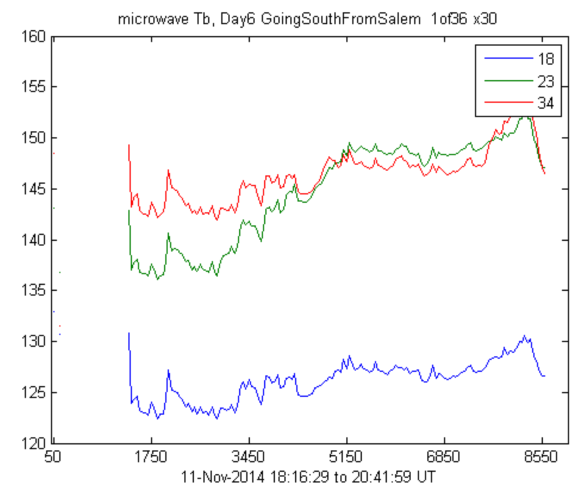


November 11, coastal example, sorted by RF frequency

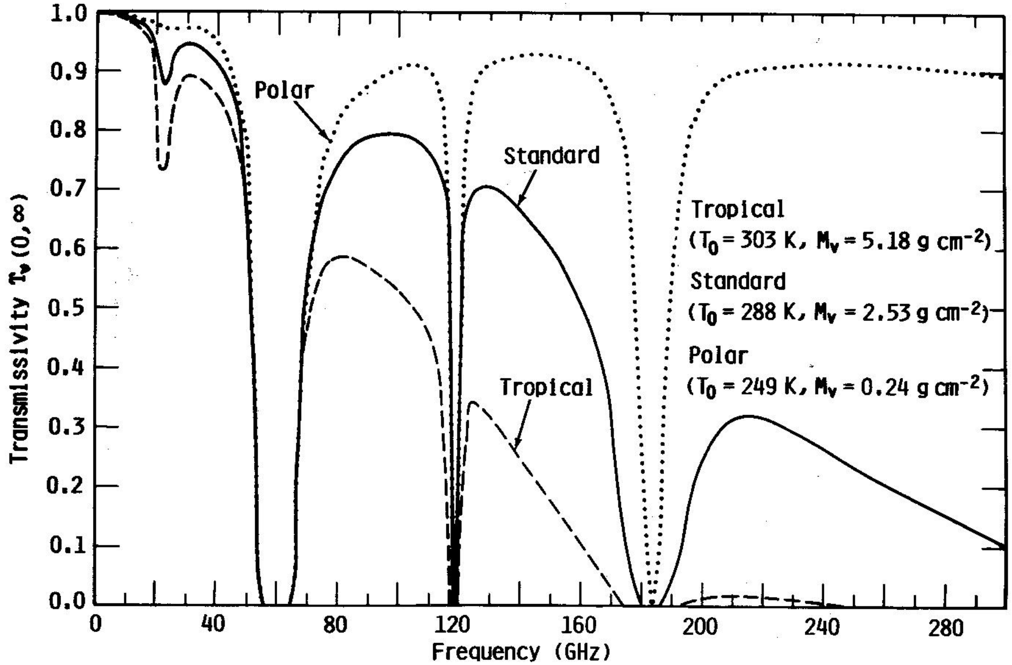
179 GHz



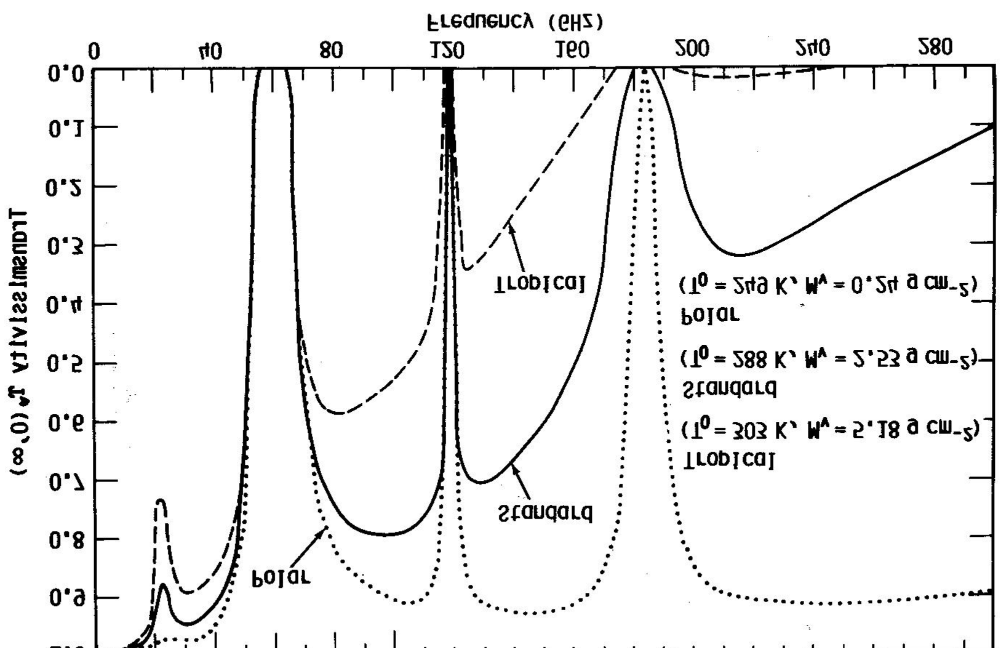
19 GHz



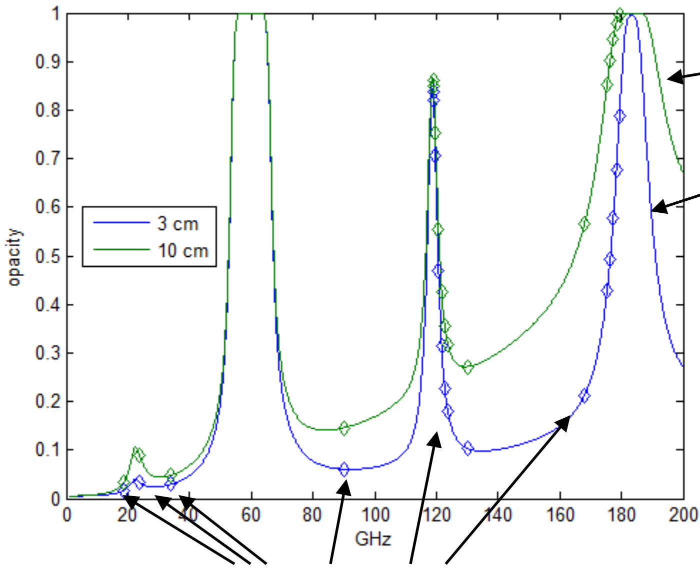
minima provide microwave Tb for water vapor retrieval= "ground truth"



Transmissivity $\tau_\nu(0,\infty)$
Frequency (GHz)
Polar
Standard
Tropical
Tropical
(T_0 = 303 K, M_v = 5.18 g cm^{-2})
Standard
(T_0 = 288 K, M_v = 2.53 g cm^{-2})
Polar
(T_0 = 249 K, M_v = 0.24 g cm^{-2})



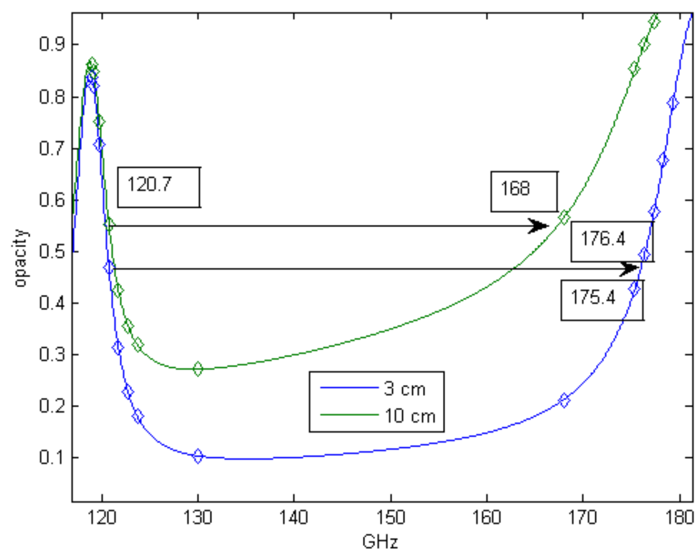
Retrieval is based on spectral models, with which oxygen is matched by opacity at given vapor level



green=10 cm wet path delay (PD)

blue = 5 cm PD

all channels



118-183

$$R_{ij} = R\left(f_i, PD_j\right) \equiv \frac{cov\left(T_{ij} - T_i, T_{90}\right)}{\sqrt{var\left(T_{ij} - T_i\right) var\left(T_{90}\right)}}$$

$$confidence \equiv \left(1 - \frac{RMSE}{PD}\right) \sum_i \frac{\partial R(f_i, PD)}{\partial PD}\bigg|_{PD=P}$$

$$0 = R(f_i, PD_i)$$

$$T_{ij} = \frac{o_{jk+1} - o_{ji}}{o_{jk+1} - o_{jk}} T_k + \frac{o_{ji} - o_{jk}}{o_{jk+1} - o_{jk}} T_{k+1}$$

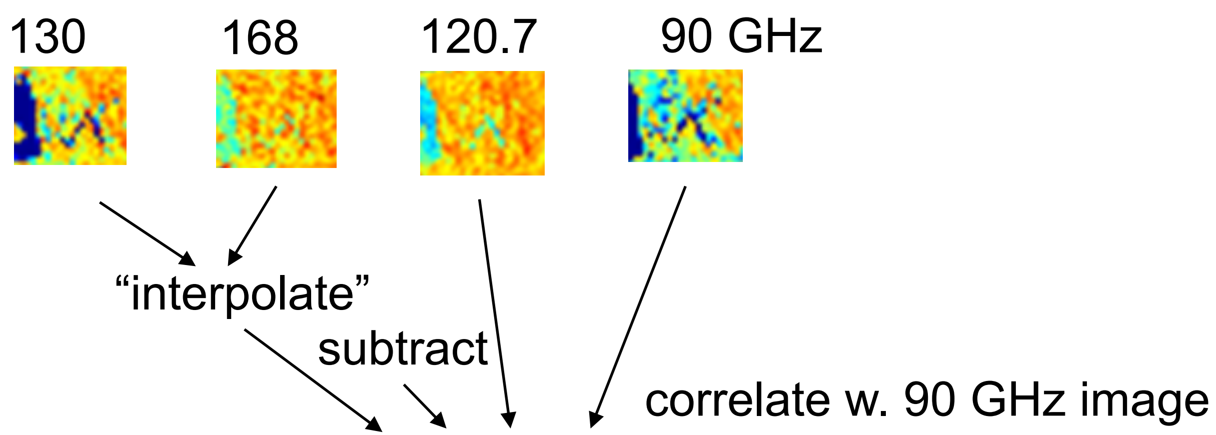
$$o_{jk} < o_{ji} < o_{jk+1}$$

$$RMSE = \sqrt{\frac{\sum_i (PD - PD_i)^2 * \frac{\partial R(f_i, PD)}{\partial PD}\Big|_{PD=PD_i}}{\sum_i \frac{\partial R(f_i, PD)}{\partial PD}\Big|_{PD=PD_i}}}$$

$$PD = \frac{\sum_i PD_i \frac{\partial R(f_i, PD)}{\partial PD}\Big|_{PD=PD_i}}{\sum_i \frac{\partial R(f_i, PD)}{\partial PD}\Big|_{PD=PD_i}}$$

step 1: Segment images into 2km x 2km cells (arbitrary choice for time being)

step 2: Compute correlation between clear surface map (e.g. at 90 GHz) and the difference between “interpolated” water channels and oxygen channel



$$R_{ij} = R\left(f_i, PD_j\right) \equiv \frac{cov\left(T_{ij} - T_i, T_{90}\right)}{\sqrt{var\left(T_{ij} - T_i\right) var\left(T_{90}\right)}}$$

What is meant by "interpolate"?

For each test case of total water vapor or path delay, PD_j, use atmospheric model to calculate three opacities, o_{ji}, o_{jk}, and o_{jk+1} at observed oxygen channel i, and vapor channels k and k+1 which satisfy

$$o_{jk} < o_{ji} < o_{jk+1}$$

then use model opacities to interpolate vapor channels to oxygen channel as

$$T_{ij} = \frac{o_{jk+1} - o_{ji}}{o_{jk+1} - o_{jk}} T_k + \frac{o_{ji} - o_{jk}}{o_{jk+1} - o_{jk}} T_{k+1}$$

Step 3:
Vary PD to locate zero crossing in

$$0 = R(f_i, PD_i)$$

PD_i in now solution which produces match between oxygen channel i, and interpolated vapor channels.

Repeat steps 2 and 3 for all oxygen channels step 4: Compute weighted mean of PD among all oxygen channels

$$PD = \frac{\sum_i PD_i \left.\frac{\partial R(f_i, PD)}{\partial PD}\right|_{PD=PD_i}}{\sum_i \left.\frac{\partial R(f_i, PD)}{\partial PD}\right|_{PD=PD_i}}$$

slope of correlation curves is proportional to signal strength, used as weighting

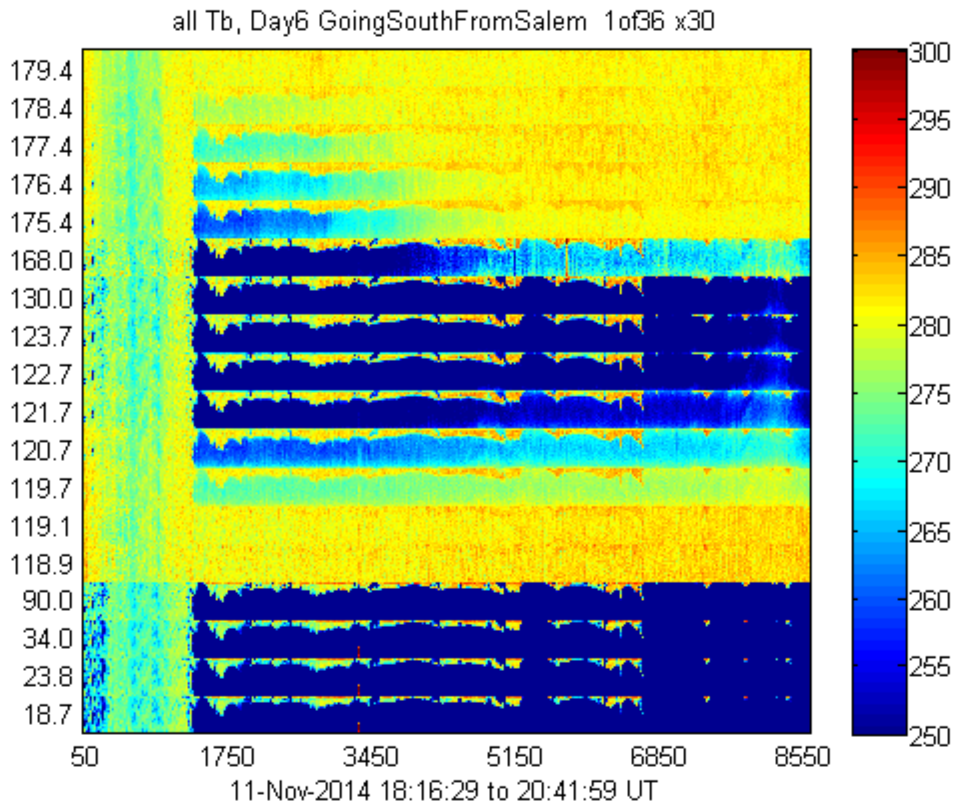
Also compute “quality metrics”

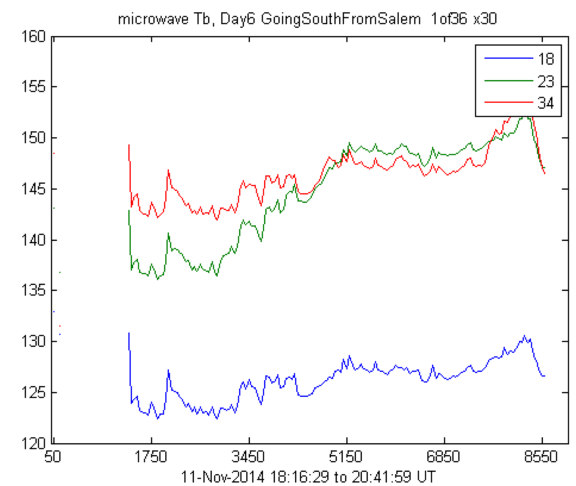
weighted RMS PD error among all oxygen channels (small= good):

$$RMSE = \sqrt{\frac{\sum_i (PD - PD_i)^2 * \left.\frac{\partial R(f_i, PD)}{\partial PD}\right|_{PD=PD_i}}{\sum_i \left.\frac{\partial R(f_i, PD)}{\partial PD}\right|_{PD=PD_i}}}$$

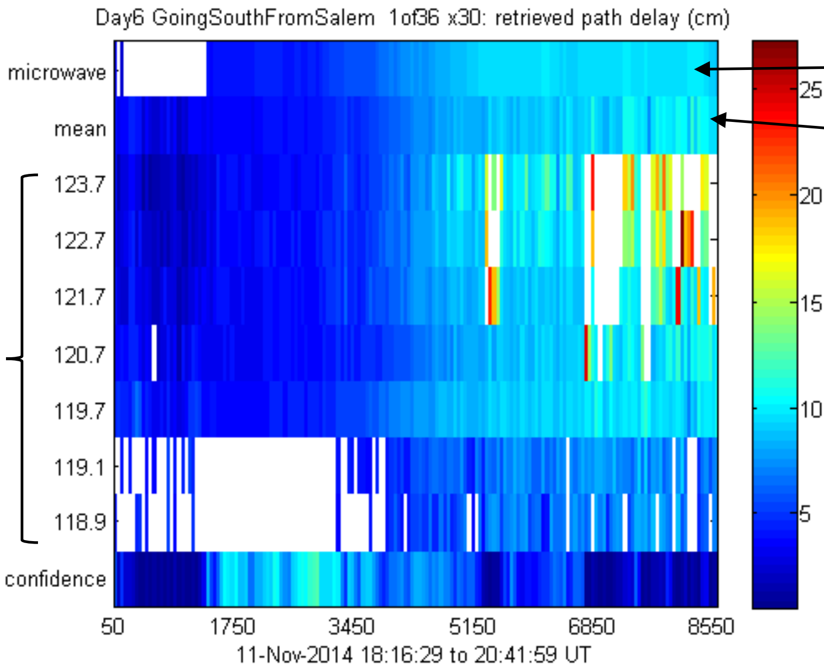
and “confidence” metric (big = good):

$$confidence \equiv \left(1 - \frac{RMSE}{PD}\right) \sum_i \left.\frac{\partial R(f_i, PD)}{\partial PD}\right|_{PD=PD_i}$$


all Tb, Day6 GoingSouthFromSalem 1of36 x30
179.4
178.4
177.4
176.4
175.4
168.0
130.0
123.7
122.7
121.7
120.7
119.7
119.1
118.9
90.0
34.0
23.8
18.7
50
1750
3450
5150
6850
8550
11-Nov-2014 18:16:29 to 20:41:59 UT
300
295
290
285
280
275
270
265
260
255
250


microwave Tb, Day6 GoingSouthFromSalem 1of36 x30
18
23
34
160
155
150
145
140
135
130
125
120
50
1750
3450
5150
6850
8550
11-Nov-2014 18:16:29 to 20:41:59 UT

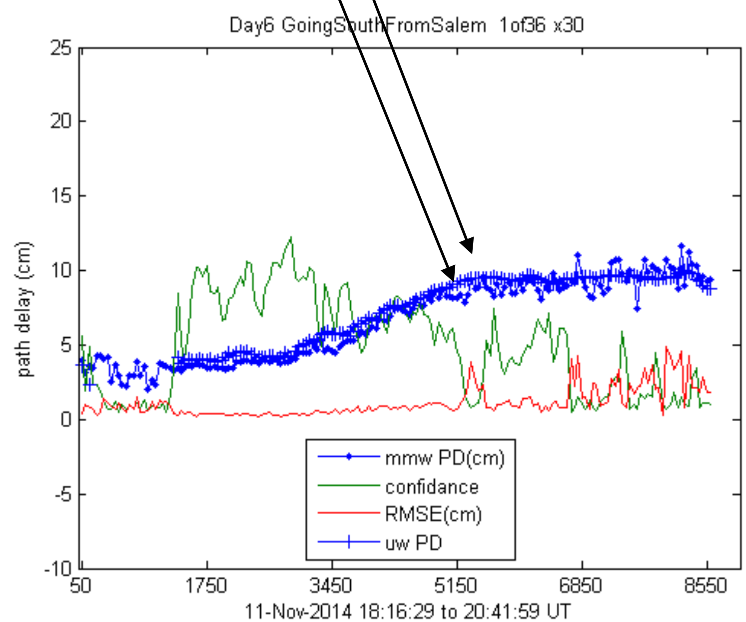
Solutions compared with 18-34 GHz microwave PD retrievals



microwave

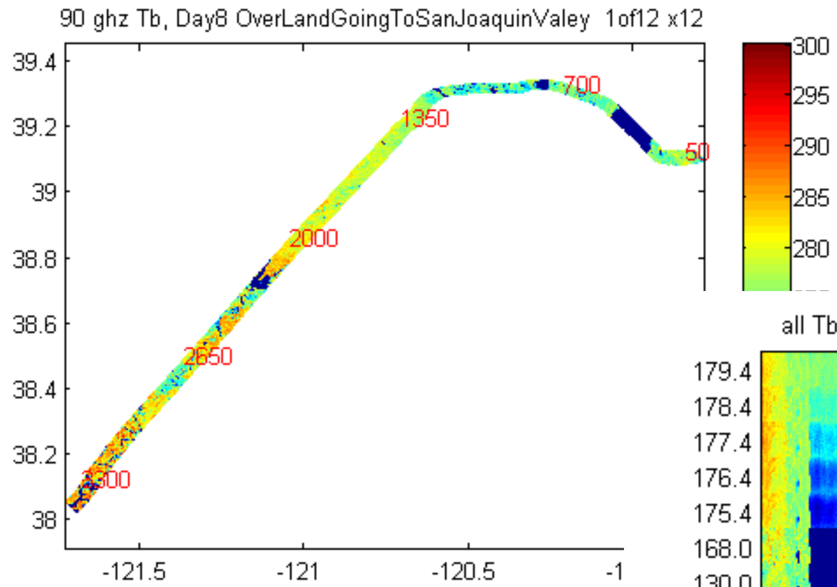
mm-wave

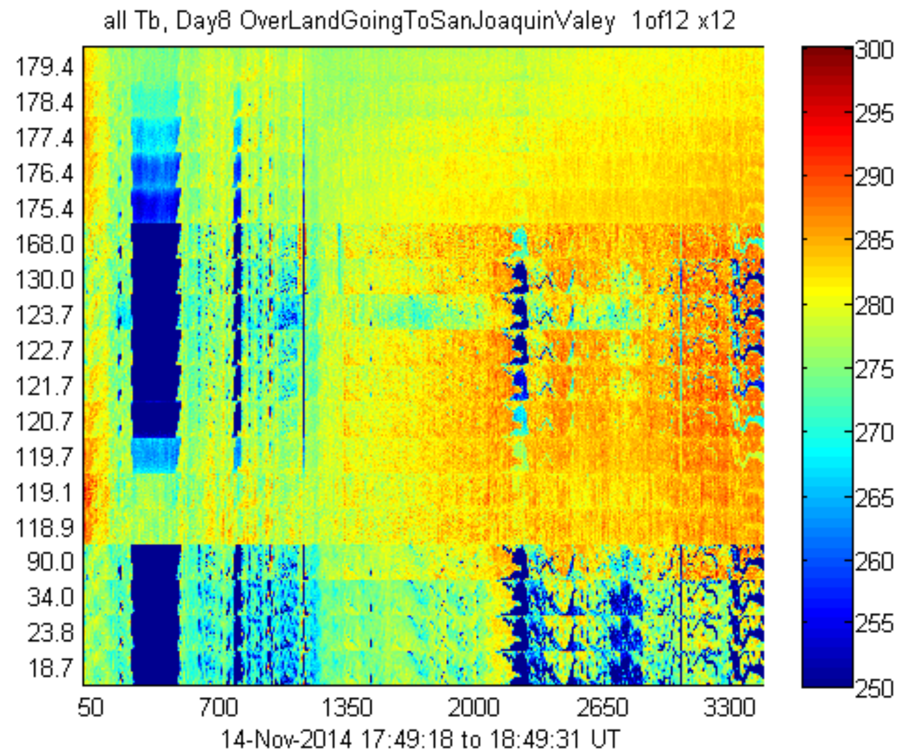
color=PD

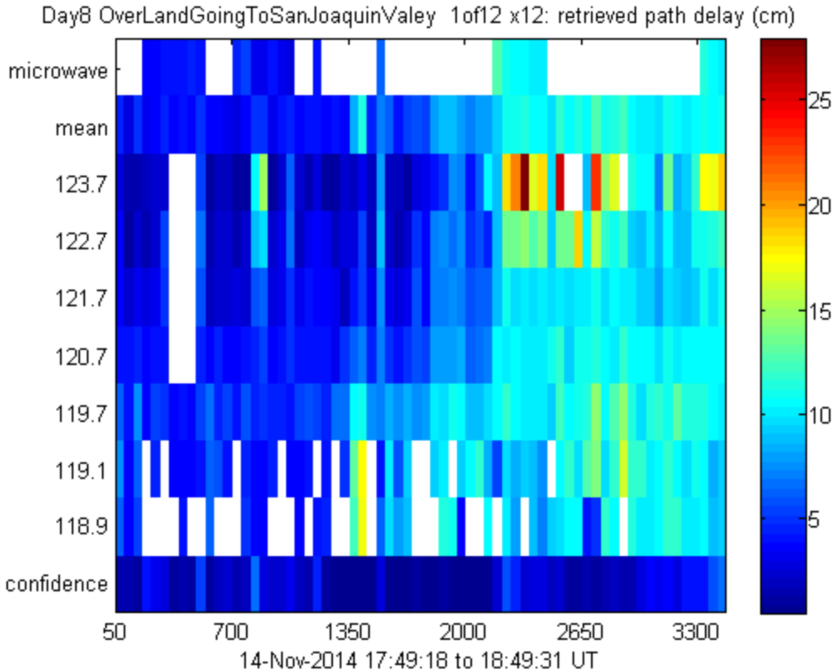


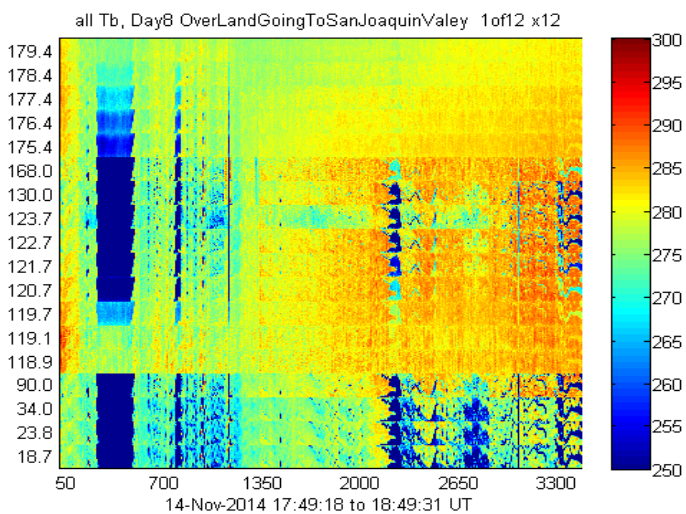
breakdown by oxygen channel

Another example: flying from Cason City NV, over Lake Tahoe, then into San Juaquin Valley, CA

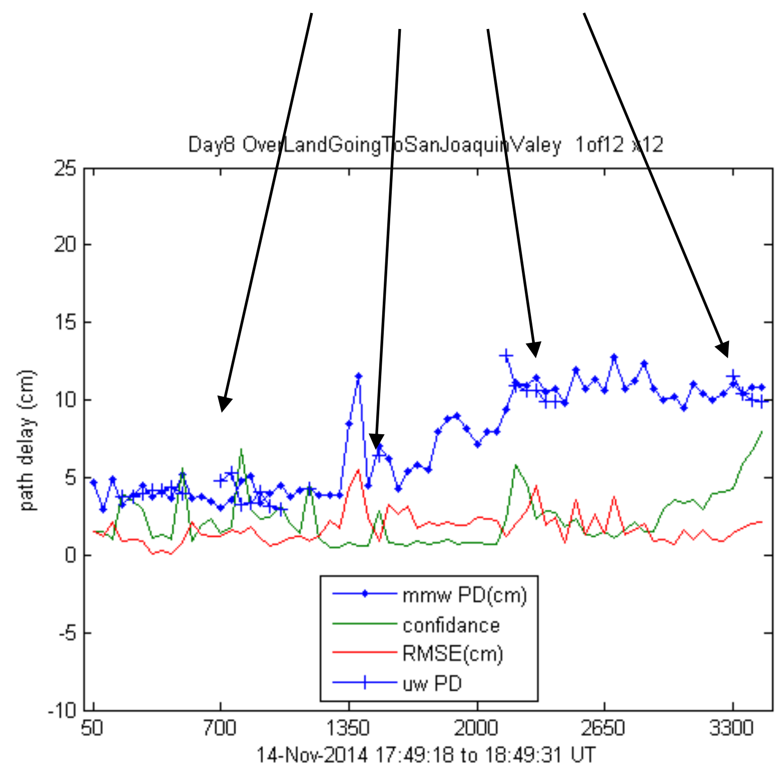








when we see open water, matchup with microwave is good!



Technical issues remaining to address:

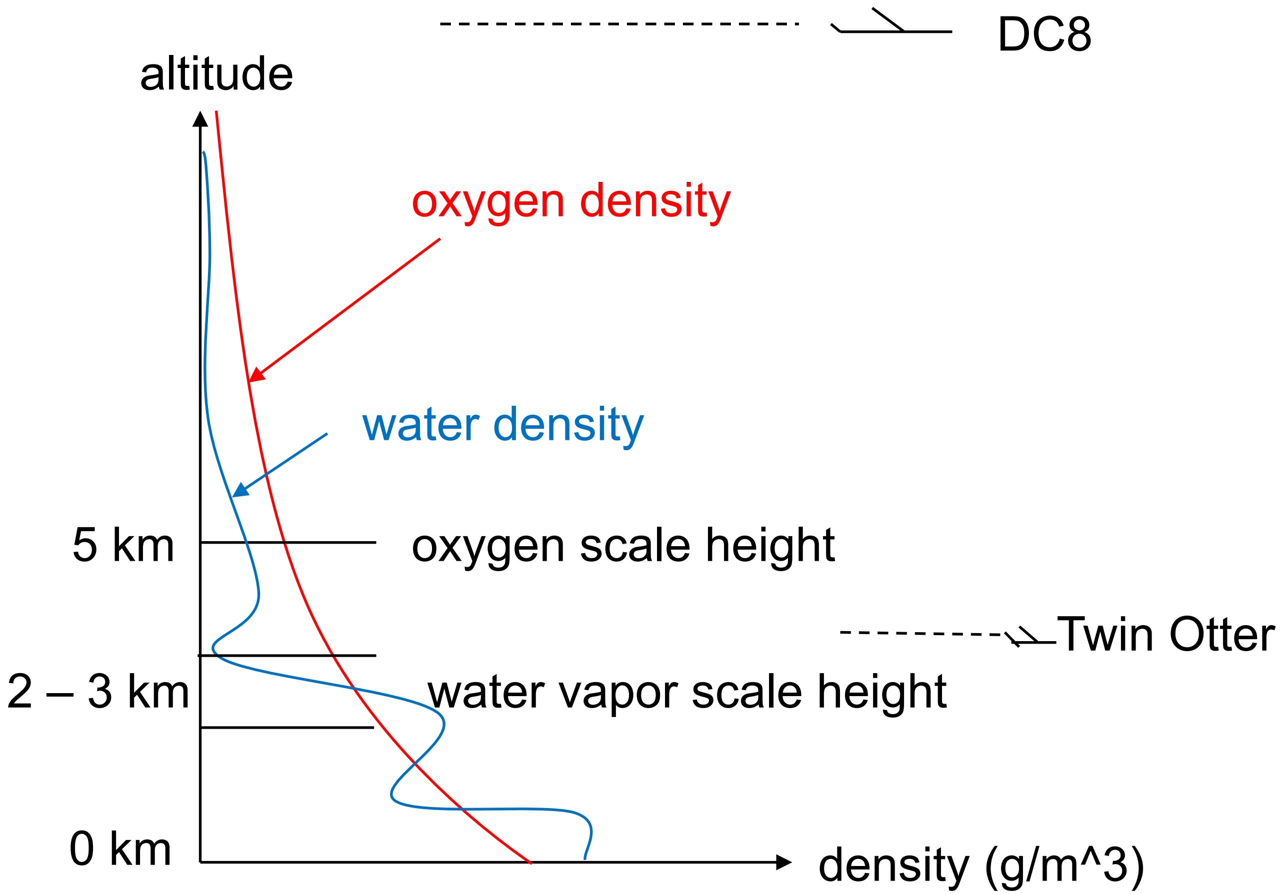
- Equal opacity but unequal downwelling temperature inevitable between oxygen and water, due to different vertical distributions. Tends to enhance scattering in oxygen bands. Multi-band comparison trends should provide correction.

- There is spectral ambiguity of continuum opacity vs PWV and path delay due to unknown vertical distribution. Mean water vs oxygen brightness temperatures, in addition to conventional soundings should be utilized to provide correction.

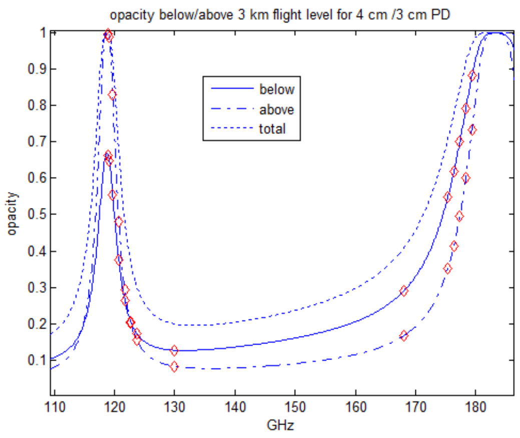
- Image segmentation presently arbitrary 2km x 2km. Better segmentation based on SNR metrics should improve spatial resolution and avoid erroneous retrievals in low SNR cases.

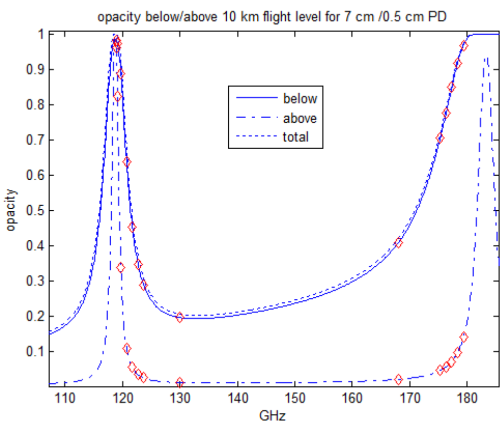
- Higher altitude needed so that majority of both oxygen and water are below observer.

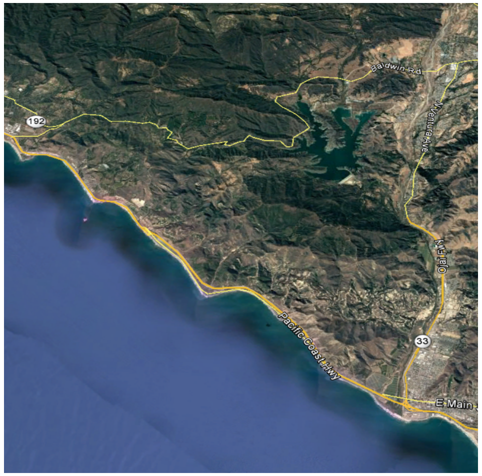
- Need to test in high water vapor cases. Likely work better by adding 60 GHz bands to compare w 90 and 130 GHz continuum
- Should add 140 and 150 GHz bands


DC8
altitude
oxygen density
water density
5 km
oxygen scale height
Twin Otter
2 – 3 km
water vapor scale height
0 km
density (g/m^3)

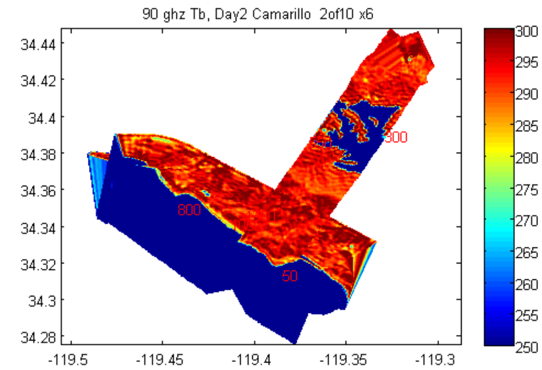
In Twin Otter, 3 km max altitude leaves a lot of water and (more problematic) *more* oxygen above aircraft



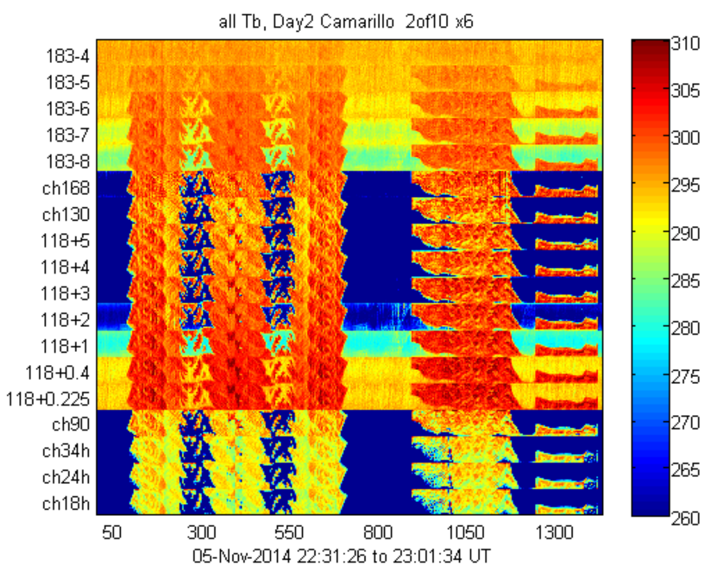




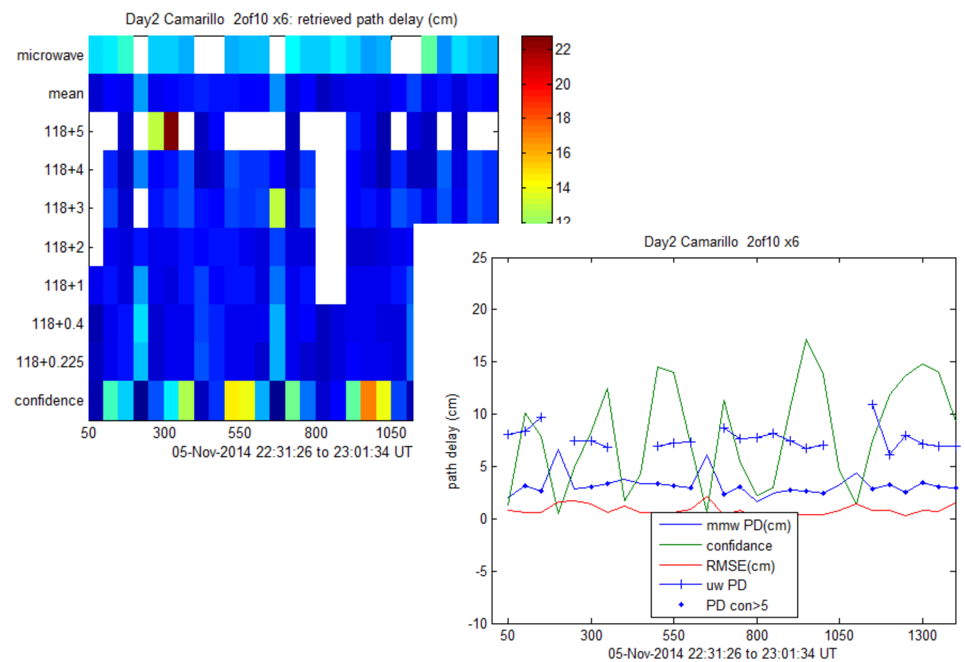
Pacific Coast Hwy
E Main
192
33



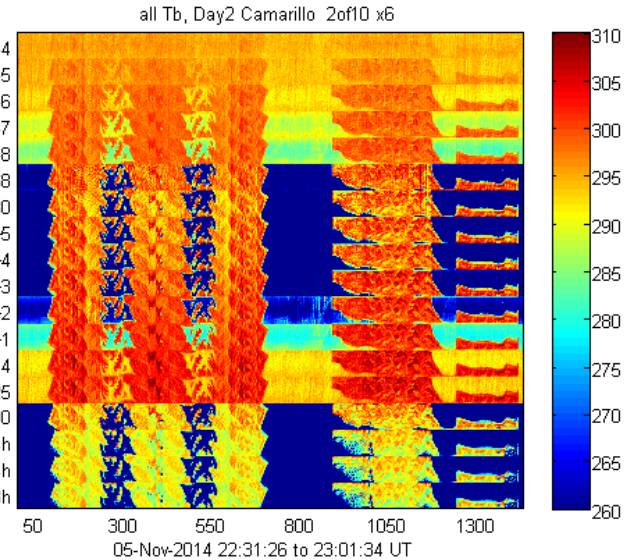
90 ghz Tb, Day2 Camarillo 2of10 x6
34.44
34.42
34.4
34.38
34.36
34.34
34.32
34.3
34.28
-119.5
-119.45
-119.4
-119.35
-119.3
300
800
50
300
295
290
285
280
275
270
265
260
255
250

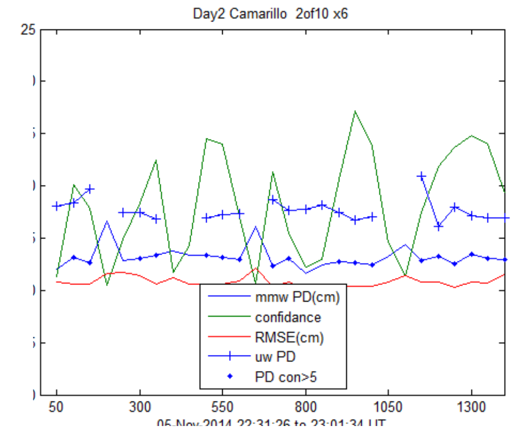


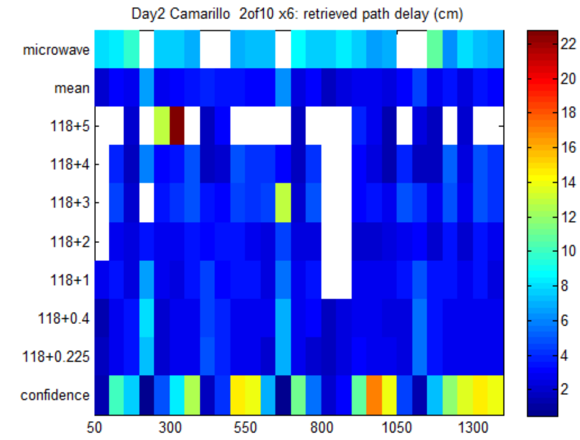
all Tb, Day2 Camarillo 2of10 x6
183-4
183-5
183-6
183-7
183-8
ch168
ch130
118+5
118+4
118+3
118+2
118+1
118+0.4
118+0.225
ch90
ch34h
ch24h
ch18h
50
300
550
800
1050
1300
05-Nov-2014 22:31:26 to 23:01:34 UT
310
305
300
295
290
285
280
275
270
265
260

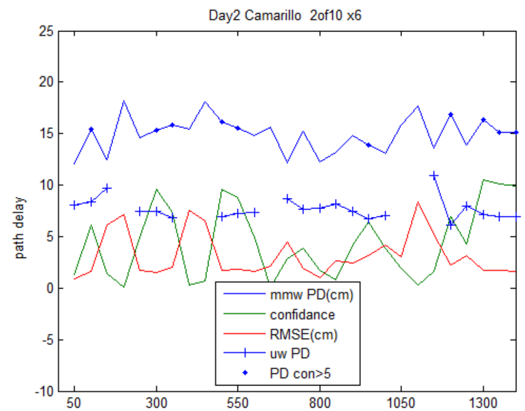


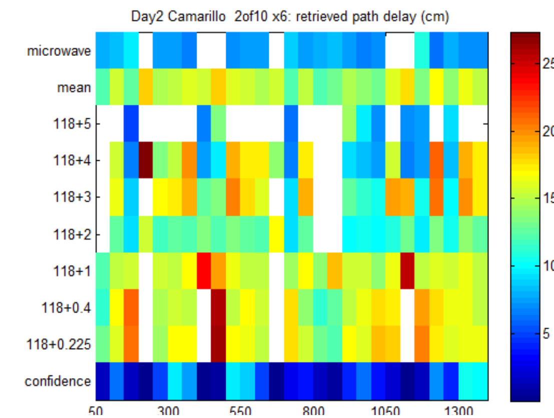
Day2 Camarillo 2of10 x6: retrieved path delay (cm)
microwave
mean
118+5
118+4
118+3
118+2
118+1
118+0.4
118+0.225
confidence
50
300
550
800
1050
05-Nov-2014 22:31:26 to 23:01:34 UT
22
20
18
16
14
12
Day2 Camarillo 2of10 x6
path delay (cm)
25
20
15
10
5
0
-5
-10
50
300
550
800
1050
1300
05-Nov-2014 22:31:26 to 23:01:34 UT
mmw PD(cm)
confidance
RMSE(cm)
uw PD
PD con>5

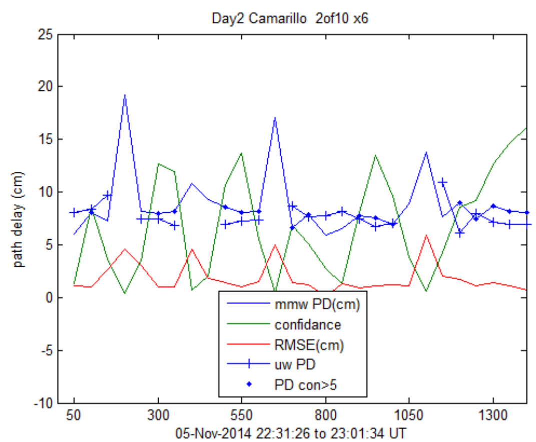

all Tb, Day2 Camarillo 2of10 x6
05-Nov-2014 22:31:26 to 23:01:34 UT

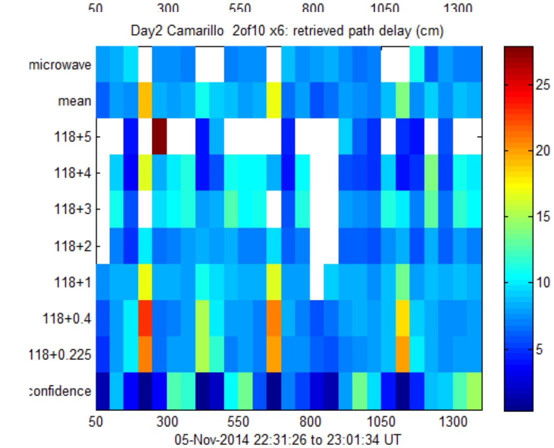

Day2 Camarillo 2of10 x6
mmw PD(cm)
confidance
RMSE(cm)
uw PD
PD con>5


Day2 Camarillo 2of10 x6: retrieved path delay (cm)
microwave
mean
118+5
118+4
118+3
118+2
118+1
118+0.4
118+0.225
confidence


Day2 Camarillo 2of10 x6
path delay
mmw PD(cm)
confidance
RMSE(cm)
uw PD
PD con>5


Day2 Camarillo 2of10 x6: retrieved path delay (cm)
microwave
mean
118+5
118+4
118+3
118+2
118+1
118+0.4
118+0.225
confidence


Day2 Camarillo 2of10 x6
path delay (cm)
mmw PD(cm)
confidance
RMSE(cm)
uw PD
PD con>5
05-Nov-2014 22:31:26 to 23:01:34 UT


Day2 Camarillo 2of10 x6: retrieved path delay (cm)
microwave
mean
118+5
118+4
118+3
118+2
118+1
118+0.4
118+0.225
05-Nov-2014 22:31:26 to 23:01:34 UT